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Study on the thermal interaction and heat dissipation of cylindrical Lithium-Ion Battery cells

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Abstract

Cylindrical Lithium-Ion Batteries have been widely used as power source for electric and hybrid vehicles because of their compact size and high power density. The battery pack is commonly consisted by hundreds of cylindrical Lithium-Ion battery cells in several strings. Because the distance among battery cells is only a few millimeters, the thermal status of battery would directly influent the current efficiency and battery life. In order to maintain proper function of the battery pack, the heat dissipation around battery cells should be deeply investigated and well controlled. This question is undeniably important and which has gained increasing attentions. Researchers have developed some models of the transient temperature distribution in Lithium-Ion battery during the discharge cycle and the thermal management on various kinds of battery packs has been studied. However, because of the compacted and complicated structure inside battery pack, the full thermal status and detail distributions are difficult to be revealed in the same time. In this work, three-dimensional simulation methods have been used to solve the above questions on the combination of several cylindrical Lithium-Ion battery cells. Existing heat generation models in Lithium-Ion battery is defined as the thermal boundary conditions. The flow and convection on the spacing has been studied. The transient thermal interactions and convections among adjacent battery cells have been investigated to explore the influences by spacing and transient heat release rules. The achieved results can be used as critical reference for designing the structures of battery pack and planning the cooling strategies.

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Keywords: Cylindrical Lighium-Ion Battery; Numerical Simulation;

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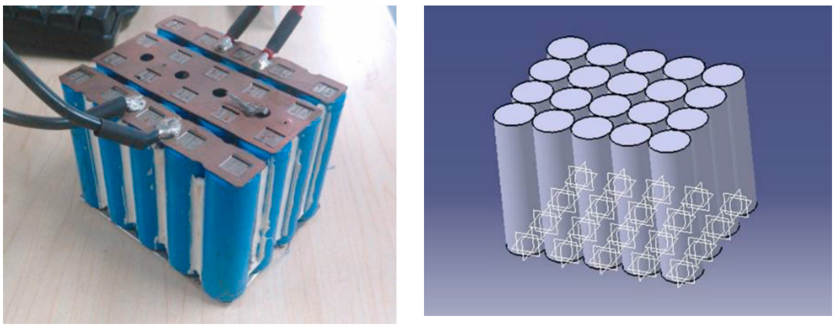
1. Introduction

Electric vehicles and Hybrid electric vehicles are developed to deal with the upcoming energy shortage and air pollution questions. The cylindrical lithium-ion batteries are widely used for its good performance in power density and current efficiency. The battery performance is greatly affected by internal temperature and the temperature differences among individual batteries [1, 2].

To explore the thermal status inside battery package, CFD simulating method has been widely used because of its applicable, well developed, and powerful. Early in the end of last century, Dickinson and Swan applied the CFD methods to analysing several battery packages in electrical vehicles [3]. They pointed out the significant negative influence on the capacity of battery package induced by temperature difference, and suggested to control the battery temperature in uniform at the range of 35~40 ^{o}C [3]. Since then, many of researchers have dedicated into controlling the temperatures of battery packages to reach the ideal range and uniform distribution. Except the typical air cooling methods [1, 4, 5], some different approaches have also been explored such as using phase change material [6], heat pipe technology [7] and micro channel tubes [8]. Moreover, experimental investigation on the cylindrical batteries has been conducted and reported by Li et al. [9]. Many of previous studies focused on the thermal management system [10, 11] and analysing methods [2, 12] to reduce the cost and time related to the design, prototyping and testing of a Li-ion battery pack. The internal flow characters of the battery modules have been pointed out as the critical part affecting the cooling performance [11, 12].

The batteries heat dissipation rules are transient and affected by many factors. Furthermore, batteries heat dissipation rules and cooling performances determine the progress of temperature elevation. In order to understand the transient thermal status and temperature variation of the battery cell during discharging, two different heat generating conditions have been applied in this work, and the simulation results have been compared and validated by the experiments. The influences by cell arrangement have also been discussed in this study, which can provide reference for designing the structures of battery pack, and planning the cooling strategies.



(a) (b)

Fig.1. The photo and scheme of mesh for the 4*5 battery package

2. Methodologies

2.1. Model Description

A 4*5 cylindrical Lithium-Ion battery package (4 lines in series, each line includes5 cells in parallel) as shown in Fig.1 (a) was studied. All the cells were located compactness, and the gap between cells were filled by thermal conductive adhesive. To simplify the simulation, the geometric model cells were established as smooth cylinders by CATIA software, the height of which was 65mm, and the diameter was 18mm illsustradted in Fig. 1. (b).

Table.1 Main parameters of 18650 battery

Parameters	Values
Rated Voltage	3.2V
Rated Capacity	1.35Ah
Equivalent Density	2018kg/m^3
Equivalent Specific Heat	1282J/(kg•K)
Volume (V_b)	1.654×10^{-5}m^3
Thermal Conductivity	Radial direction： 0.9W/(m•K) Axial direction：2.7 W/(m•K)

2.2. Simulating Models

The heat dissipation way of this battery package in test procedure was natural convection. Therefore, a triple size region outside of battery package was taken as air region.

Mesh was generated by Hypermesh program. Three kinds of meshes with different density were established and compared. After the mesh irrelevant analysis, the model including about 1.6 million unstructured tetrahedral meshes was selected. In order to analyse the thermal status in battery cells and study the temperature variation characteristic, the three-dimensional transient flows were numerical simulated by ANSYS FLUENT 16.5. The battery cells studied in this paper were 18650 batteries, and the corresponding parameters provided by the cell company were listed in Table 1.

The bottom of package and air region was set as isolated wall, the surface at the top of air region was set as pressure outlet, and the surfaces in the side of air region were pressure inlet, where the initial pressure was zero. The pressure-based solver was selected, and the pressure discretization scheme was PRESTO!. Time step was 05.s, and initial temperature was 293K.

Table 2. The Heat Generation Rate of Single Cell.

Number	Discharge Rate	Current of the Cell	Heat Generation Rate
1	1C	1.35A	5318W/m^3
2	2C	2.70A	19452W/m^3

2.3. Heat Generating Calculation

According to the heat generation theory by Noboru Sato [13] in most of the conditions, the thermal generation factors would be decomposed to three key elements: reaction heat value Q_r, polarization heat value Q_p, and Joule heat value Q_J. Therefore, the total generated heat Q_t could be written as Eq. (1).

In the charging progress, if the charge rate was very small, the polarization heat Q_p was in a quite small value, the battery was in a heat absorption condition at the beginning of charge, which could be kept in a low temperature. But when the charge rate increased, the Q_p and Q_J would be elevated at the same time. In discharging progress, the battery temperature would be raised in a non-linear trend. The heat generating rate of single cell in discharging could be calculated by Bernadi equation [14], as shown in Eq. (2), where q represented the battery heat generating rate per unit time and volume. I was the current through battery, it was positive in charging, and negative in discharging. V_b was the effective calculating volume of the individual battery cell. U and U_0 were the tested voltage and open-circuit voltage of the battery cell respectively. T was the battery temperature in the current. $\frac{d\,U_0}{d\,T}$ was a parameter related to the electrochemical reaction, named as temperature coefficient.

$$Q_t = Q_r + Q_p + Q_J \tag{1}$$

$$q = \frac{1}{V_b}\left[I^2R_0 + IT\frac{d\,U_0}{d\,T}\right] \tag{2}$$

The internal resistance could be set as 0.04Ω, $T\frac{d\,U_0}{d\,T}$ could be set as 0.01116V. Then the heat generating rate at different discharging conditions could be calculated to constant value, listed in Table.2.

3. Tests and comparisons

The internal temperatures of the battery package were measured to evaluate the precision of simulations. Eight thermal couples after calibration were inserted into the battery package, and the locations were numbered and shown in Fig.2.

At first, adjust the ambient temperature to 293K. Fullly charge the batteries, then discharge the battery package in the rate of 1~5C, record and save the temperature values every 1 second through the temperature collect system. Some of the test results were listed in Fig.3.

When the time increased, the temperature was elevated in a non-liner trend. The internal temperture of the battery module (Point 1 and 2) was obvious higher than the outside temperature.

To compare with the simulating results, temperature of the key points 1,2,3 by tests and simulations were selected and listed as below. Fig.4 depicted these temperature variations.

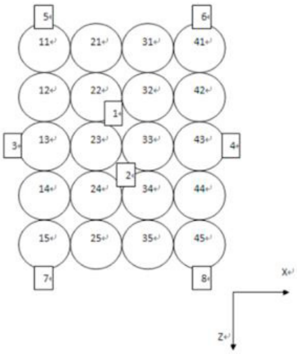


Fig.2. Number of the cells and locations of temperature sensors

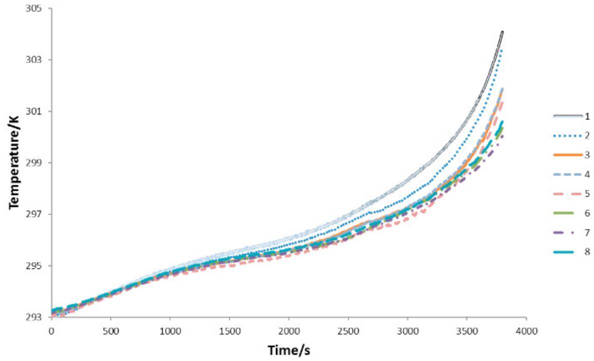


Fig.3. The temperature variation on the time when be discharged at 1C by test

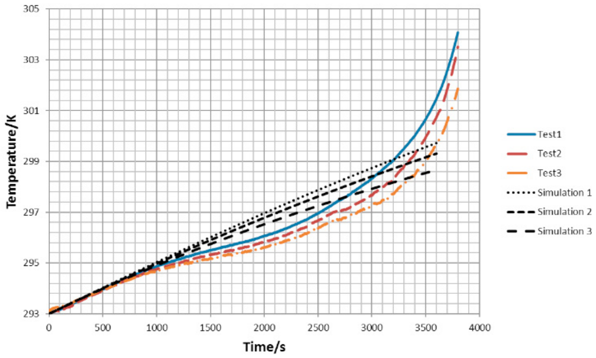


Fig. 4. The comparison of test and simulated temperature at point 1, 2, 3 when be discharged with 1C

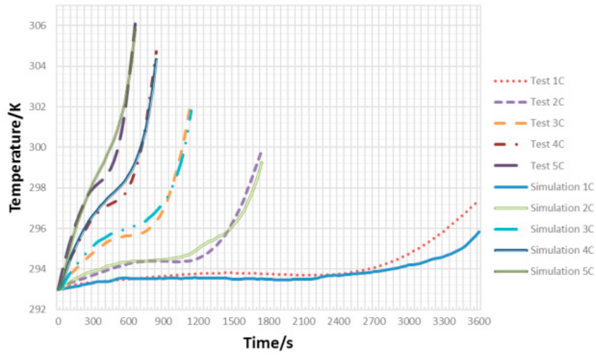


Fig. 5. The temperature development by tests and simulation at different discharge rates

From this figure, the temperatures calculated by simulations were developed in a liner trend, which was totally different with the trend of tested temperature variasions. There were big gaps between test results and simulating results when the time was larger than 1000 seconds. And with the time increased, the differences turned to huge. These differences were derived from the calculation of heat generation rate in simulation. Based on Table 2, the transient thermal status was neglected, heat generation rate was set as constant in the whole discharge progress. However, in actual usage, the heat generation rate would increased with the drop of SOC (State of Charge) level. When the discharge time past, the SOC level reached to a particular low value, lots of heat would be generated in battery, then the temperature increased sharply, as measured in the experiments.

To solve this question, improve the simulating precision, a new method in calculating the heat source should be developed. Where the discharge rate, discharge time and SOC level should be considered to evaluate the transient heat genaration.

4. Optimised method to calculate the heat generation rate

In previous simulations, the battery cell was defined as a uniform heat generation body, and the heat generation rate was constant, only affected by the discharge current, which was differed from the actual battery thermal condition. Thus a computational scheme was developed, and the progress was introduced as below:

(1) Test and record the battery internal resistance, the electrodynamic force, and the temperatures at different charging/discharging rate

(2) Propose the mathematical models for the relationship of the Ohmic resistance and cell temperature and SOC level, the relationship of the Polarization resistance, cell temperature, and SOC level, the relationship of the electrodynamic temperature variation coefficient with the SOC level by polynomial fitting;
(3) Substitute the previous relationship into equation 1 after the unit transform, then deduce the equation of heat generation rate with the discharge rate, temperature, and SOC level;
(4) Program the UDF code about the transitional heat generation rate, adopt it as the heat source of batteries in CFD simulations.

Fig. 5. displayed the average temperature developments by tests and simulations at different discharge rates. After optimization, the trend of temperature elevation by simulating was similar to the trend of test results, the error at most of the conditions was obviously decreased also. It proved that the optimized evaluation on the heat generating rate was effectiveness in studying the thermal status of battery modules.

5. Effects of different arrangements

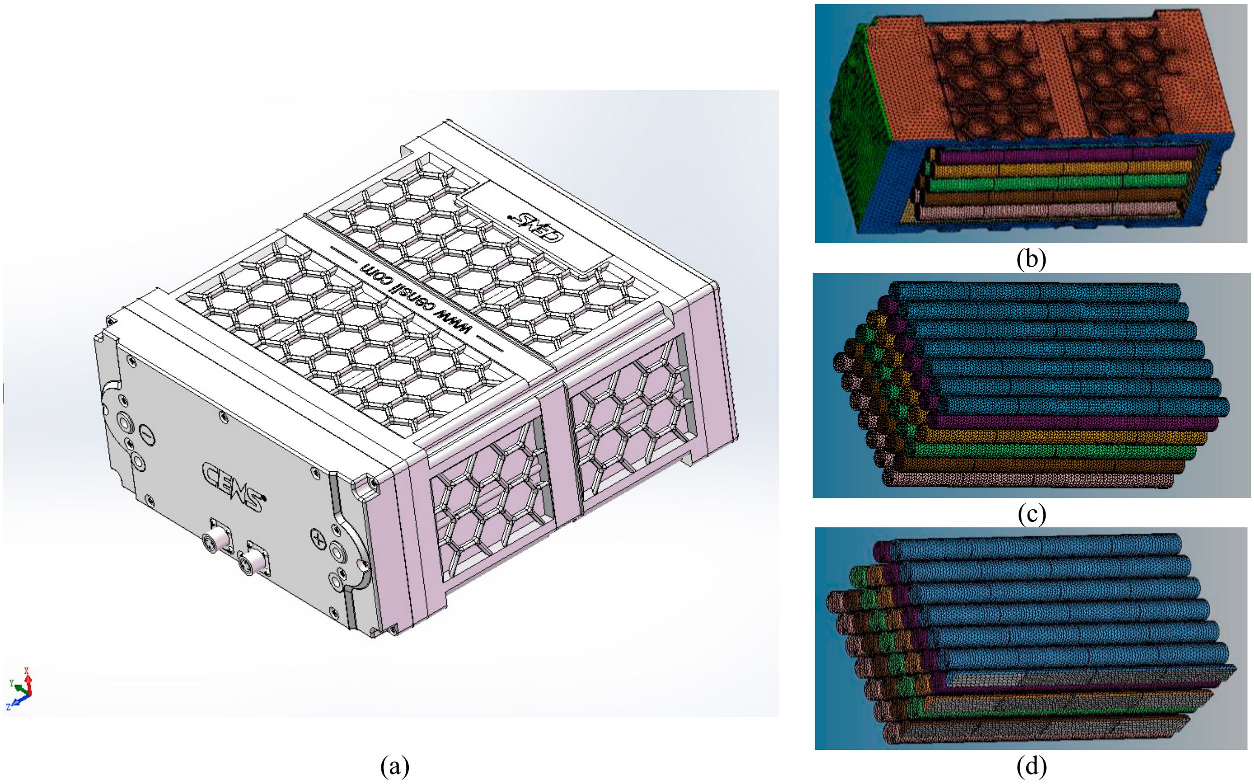


Fig.6. The scheme of a particular battery package including 6*14*14=336 cells. (a) 3-D model; (b) mesh in the most of solid regions; (c) cells in line; (d) cells in staggered

Hundreds of battery cells were assembled together shown in Fig.6, which was managed as a small system. Battery cells were arranged very close to minimize the package volume as small as possible. Outside of the battery cells, there was a hermetical aluminium alloy box. The heat dissipation way was natural convection. The heat generated by cells was transferred to the box by internal air, then dissipated through the wall.
There were two different arrangements of these battery cells: in line (Fig.6c) or in staggered (Fig.6d). To compared the batterie thermal conditions in these two arrangements, three-dimensional models were established, numerical studied, and analysed. About 2.57 million unstructured tetrahedral meshes were generated, as shown as in Fig.6.

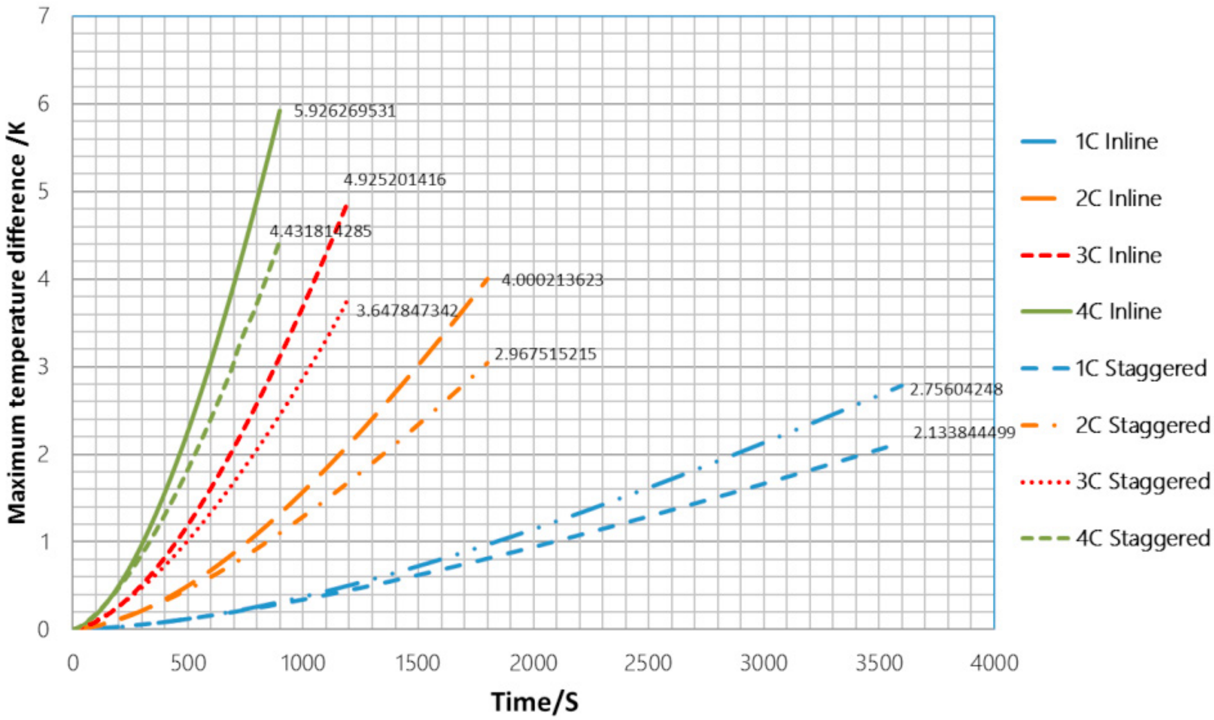


Fig.7. The Maximum increasing temperatures at different arrangements

Because of the complicated progress and large time costs in calculating the heat generating rate in optimized method, simplified heat generation rate was used in the simulations.

In order to calculate the heat generating rate some empirical values have been adoptted, for example R_0 was set at 40mΩ, $T\frac{dE_0}{dT}$ as $0.01116V$, volume of battery as $1.654 \times 10^{-5}m^3$. The heat generating rates at different discharge rates were listed as Table.3.

Moreover, the maximum temperature elevations of both models at different discharge rates were listed in Table 3. From this comparison, it could be concluded that the maximum temperature in staggered model was larger than the one in inline model. The inline structure might be superior in total heat dissipation.

The maximum temperature differences at different arrangements was shown in Fig.7. From this figure, the maximum temperature in parallel package was higher than the maximum temperature in interlaced package. Which indicated the interlaced arrangement would have some positive effects on the thermal status of battery packages.

Table 3 The heat generation rates and maximum temperature elevations at different discharge rates

Discharge rates	Heat generation rate（W·m^{-3}）	Inline (K)	Staggered (K)
1C	5318	7.36	7.38
2C	19452	13.52	13.53
3C	42400	19.65	19.66
4C	74163	25.79	25.95

6. Conclusions

This paper studied a 4×5 battery module by numerical simulations using two different calculation methods for the heat generation rate. In the first model, the heat generation rate was originally defined as constant. The simulation results of the first model shown great difference compared with the experiment data. It was found that the trend of transient thermal status was determined by the definition of source term.

The second model optimised the calculation methods for the heat generation rate. Based on the relationship of the Ohmic resistance, cell temperature, and SOC level, the relationship of the Polarization resistance, cell temperature, and SOC level, the relationship of the electrodynamic temperature variation coefficient with the SOC level, a fitting formula was established and applied in UDF. With adopting this UDF, the simulation results shown good agreement with the test data.

Two 336 battery cell packs in different arrangements were further studieded to explore the influence of different structure. Results indicated the maximum temperature value in staggered model was a little higher than the one in inline model, but the temperature differences internal of inline battery pack was lower than the one in inline model. It indicated the staggered arrangement can achieve better performance in temperature uniform distribution.

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Biography

Dr Yiji Lu, born in June 1989, is currently a research associate in Newcastle University. He graduated from Shanghai Jiao Tong University in 2011 for his bachelor degree, he conducted his M.Phil. and Ph.D. in Newcastle University in 2012 and 2016. His Ph.D. program was fully sponsored by EPSRC and was awarded the '2015 Chinese Government Award for Outstanding Self-financed Students Abroad' from China Scholarship Council. His research interests include but not limited to advanced waste heat recovery technologies, engine thermal management, advanced engine development, engine emission technologies, chemisorption cycles and expansion machines for power generation system. He has been regularly invited to review the manuscripts for the scientific journals including Applied Energy, Applied Thermal Engineering, Energy (the International Journal), and Energy for Sustainable Development.

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